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14. ABSTRACT

This DoD HPC Challenge project is a crucial component of an effort to develop a data-assimilative 1/320 global ocean nowcast/forecast system, which includes the associated basic research and exploratory development. The need for 1/320 resolution (-3.5 km at mid-latitudes) has been demonstrated through extensive research, including essential contributions from our FY97 and FY98/00 DoD HPC Challenge projects. The ocean model, after 30 years of climatological spinup, was run interannually spanning the period 1979-present Data assimilation experiments are currently underway. Transition of this system to operational use at the Naval Oceanographic Office (NA VO) is planned for later in 2003.

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1/32° Global Ocean Modeling and Prediction

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Abstract

This DoD HPC Challenge project is a crucial component of an effort to develop a data-assimilative 1/32° global ocean nowcast/forecast system, which includes the associated basic research and exploratory development. The need for 1/32° resolution (~3.5 km at mid-latitudes) has been demonstrated through extensive research, including essential contributions from our FY97 and FY98–00 DoD HPC Challenge projects. The ocean model, after 30 years of climatological spinup, was run interannually spanning the period 1979–present. Data assimilation experiments are currently underway. Transition of this system to operational use at the Naval Oceanographic Office (NAVO) is planned for later in 2003.

1. Introduction

This DoD HPC Challenge project is a crucial component of an effort to develop a data-assimilative 1/32° global ocean nowcast/forecast system, which includes the associated basic research and exploratory development. The need for 1/32° resolution (~3.5 km at mid-latitudes) has been demonstrated through extensive research, including essential contributions from our FY97 and FY98–00 DoD HPC Challenge projects. These projects also helped establish 1/16° (~7 km at mid latitudes) as the minimum resolution needed for a fully eddy-resolving global ocean model. Major improvement was obtained with an increase to 1/32° resolution, but only modest additional improvement with a further increase to 1/64° resolution.

Our previous DoD HPC Challenge projects were a critical component of the effort to develop a 1/16° global ocean nowcast/forecast system. That system has been transitioned to the Naval Oceanographic Office (NAVO), Stennis Space Center, MS where it has been running in real time since 18 Oct 2000, and became an operational product on 27 Sept 2001. This 1/16° system includes assimilation of altimeter sea surface height (SSH) data from three satellites and sea surface temperature (SST) from satellite IR. It clearly demonstrates the ability to track the evolution of oceanic eddies and the meandering of ocean currents and fronts, which have space scales O(100 km). At least 30-day forecast skill has also been demonstrated globally. Results can be viewed on the web at http://www.ocean.nrlssc.navy.mil/global_nlom.

The full resources of a large three-year HPC Challenge project was required to permit the transition later in 2003 of a 1/32° global ocean nowcast/forecast system to NAVO. That includes (a) multi-decade 1/32° global ocean simulations which are needed to assess the realism and dynamics of the model and for the generation of statistics and a model mean SSH needed in the data assimilation, (b) ocean nowcast experiments with data assimilation into the model and (c) ocean forecast experiments initialized from the experiments with data assimilation.

Applications for this nowcast/forecast system include assimilation and synthesis of global satellite surface data; ocean prediction; optimum track ship routing; search and rescue; anti-submarine warfare and surveillance; tactical planning; high resolution inputs for other models and shipboard environmental products; environmental simulation and synthetic environments; observing system simulations; ocean research; pollution and tracer tracking and inputs to water quality assessment.

The NRL/NAVO global ocean prediction effort is a participant in the multinational Global Ocean Data Assimilation Experiment (GODAE) which is designed to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products with a customer base (International GODAE Steering Team, 2000). Our effort is represented on the U.S. and

International GODAE Steering Teams. GODAE is scheduled for 2003-2007 with pilot programs in 2000–2002.

2. Problem and Methodology

Global ocean modeling and prediction is one of the original Grand Challenge problems that, by definition, require a Tflop/s (sustained) performance. NRL's approach to this problem seeks to reduce the cost via a careful choice of algorithms and the use of a Lagrangian vertical coordinate. Because the NRL Layered Ocean Model (NLOM) has a factor of 10s–100s advantage in computer time requirements over other global and basin-scale ocean models, we can "solve" this problem on a computer sustaining O(100) Gflop/s. The NRL modeling strategy is discussed in the Hurlburt and Wallcraft (2000) case study for the Smithsonian, which uses the case studies as one means of developing a history of information technology and its benefits to society. NLOM (Wallcraft, 1991; Wallcraft and Moore, 1997) is written in the tiled data parallel programming style. It is scalable using: (a) autotasking, or (b) data parallel Fortran, or (c) SHMEM library calls, or (d) Message Passing Interface (MPI) library calls and thus is portable to a wide variety of computing platforms.

A critical issue in forecast system design is determining the resolution required. Ocean models require finer resolution and more computer time than atmospheric models in part because the space scales for variability due to flow instabilities (oceanic mesoscale eddies vs. atmospheric highs and lows) are about 20–30 times smaller than found in the atmosphere. We need to resolve the oceanic eddy space scale very well because (1) it is relevant for most of the Navy applications listed earlier, (2) these models need to provide high resolution boundary conditions for even higher resolution coastal models, (3) upper ocean—topographic coupling via flow instabilities has a major impact on the pathways of many upper ocean currents (including mean pathways) and very fine resolution of the flow instabilities is required to get sufficient coupling (Hurlburt, et. al., 1996; Hurlburt and Metzger, 1998; Hogan and Hurlburt, 2000; Tilburg et. al., 2001), (4) very fine resolution is required to obtain (a) inertial jets and sharp oceanic fronts which span major ocean basins as observed (Hurlburt, et al., 1996) and (b) the associated nonlinear recirculation gyres which affect the shape of large-scale ocean gyres (Hurlburt and Hogan, 2000), (5) it is necessary to resolve small islands and narrow passages which affect current pathways and current transports in many regions (e.g., Metzger and Hurlburt, 2001), (6) in data assimilative mode we do not want the ocean model to "fight" the data because the natural behavior of the ocean model is inconsistent with the observations (Hurlburt, et al., 2000), and (7) a very high horizontal resolution model is needed to help get an accurate mean sea surface height field to add to the deviations obtained from satellite altimetry (observations alone do not provide sufficient resolution to do this).

The need for 1/32° resolution (~4 km) has been demonstrated through extensive research, including essential contributions from our FY97 and FY98–00 DoD HPC Challenge projects as well as non-challenge HPC usage (e.g., the publications cited above). These projects also helped establish 1/16° (~7 km at mid latitudes) as the minimum resolution needed for a fully eddy-resolving global ocean prediction system. Major improvement in model simulation skill was obtained with an increase to 1/32° resolution, but only modest additional improvement with a further increase to 1/64° resolution (Hogan and Hurlburt, 2000; Hurlburt and Hogan, 2000).

The 1/32° global ocean prediction system represents a doubling of the resolution and an 8-fold increase in computer time requirements over the 1/16° global system transitioned to NAVO in 2000. Therefore, the full resources of a large three-year HPC Challenge project were required to permit transition of a 1/32° global system to NAVO in 2003. In the first step climatological atmospheric forcing was used to extend the equilibrated 1/16° global model at 1/32° resolution for 30 model years until it was re-equilibrated, a step that was completed in late 2001. In addition to re-equilibration, the climatological simulation was used to fix problems that arose, optimize model parameters, assess the impact of the resolution increase on model realism and dynamics and to perform climatological model-data comparisons.

The climatological simulation was followed by a simulation forced interannually by two different atmospheric products. This simulation was first run with ECMWF atmospheric forcing for the period 1979–1995 using the 6-hourly ECMWF reanalysis. The ECMWF product is widely acknowledged as the best available and is available over an interval long enough to include a wide range of variability. In particular, it extends back far enough to include the 1982–83 El Niño (with some lead-time), an El Niño which had at least a decadal impact on Pacific Ocean variability (Jacobs et. al., 1994). In 1991 this simulation was continued using FNMOC NOGAPS forcing and was run through the present. In all of the interannual runs the temporal mean of the wind forcing is replaced by the annual mean from the Hellerman and Rosenstein (1983) (HR) wind stress climatology used to force the climatologically forced simulation. This minimizes additional spin-up effects when the interannual forcing is started and it avoids the need for separate spin-ups for different wind products. Overall, HR wind stress forcing gives the most realistic model means of the wind products we have tried.

The interannual simulations were used to assess the model realism and dynamics in representing atmospherically forced variability on a wide range of time and space scales and dynamical regimes. The interannual simulations are critical for comparisons to data sets taken over specific time frames. They also help us investigate the model's ability to produce a wide range of oceanic variability. In addition, interannual simulations attract greater interest from researchers outside of NRL. The 1/32° model resolution is an unprecedented opportunity to study regional oceanography and dynamics at high resolution in the context of the global ocean circulation (which is also influenced by the high resolution). Major scientific objectives include investigating (a) the interactions between the thermohaline component of the circulation, the wind-driven component and the mesoscale eddy field; (b) the influence of upper ocean—topographic coupling via baroclinic instability on the preceding and on the pathways of upper ocean currents; (c) the influence of the global ocean circulation on regional dynamics; and (d) Low Latitude Western Boundary Currents (LLWBCs) and their roles in interbasin exchange.

The interannual simulation has been followed by (1) ocean nowcast experiments with data assimilation, and (2) ocean forecast experiments initialized from (1) later in FY03. All of the data assimilation experiments are initialized from the FNMOC NOGAPS forced simulations and will use this forcing during data assimilation and forecasting experiments except for forecasting experiments where the atmospheric forcing is relaxed towards climatology during the forecast. This will be done to assess the impact of atmospheric forcing on oceanic forecast skill as a function of time, region and dynamical regime. In addition to comparison with the ECMWF-forced simulations, the FNMOC forced simulations will be compared with data-assimilative runs to assess the impact of the data assimilation. In all cases these comparisons will be done in the context of model-data comparisons using contemporaneous data.

The data assimilation experiments are being used to improve and optimize data assimilation techniques at 1/32° over a wide range of ocean regions and dynamical regimes. The interannual simulation was used to provide statistical parameters for the subsurface statistical inference technique (Hurlburt et. al., 1990) used to project the surface data downward to update the lower layers of the ocean model. It also provides a high resolution global temporal mean SSH which must be added to the SSH deviations obtained from satellite altimetry. Surface dynamic height from hydrographic climatologies is inadequate for this purpose. NLOM is designed to provide accurate mean sea surface height. It agrees well with the hydrographic climatologies but provides a much sharper depiction of mean currents. Because of the preceding and in addition, the importance of model dynamical

interpolation skill in assimilating ocean data, and the model skill in converting atmospheric forcing into oceanic information, the ocean model is an integral component of the data assimilation scheme. Model simulation skill is also essential for skillful 30-day forecasts. The forecast experiments will be used to assess model forecast skill as a function of region and dynamical regime. In addition, forecast skill will be used as one of the gauges to assess data assimilation skill. Thus, research, development, test and evaluation running of the 1/32° global model with and without data assimilation and running it in forecast mode from data-assimilative states are essential for transition of a successful 1/32° global NLOM nowcast/forecast system to operational use at NAVO. Finally, an assimilation experiments run from 1993 (the start of TOPEX/POSEIDON altimeter data) up to near real time is planned to assess data assimilation and forecast skill over a wide range of variability in each region. This assimilation run will allow researchers to follow the evolution of observed oceanic anomalies with unprecedented resolution and with space-time continuity that is generally not possible using raw data.

3. Results

After 30 years of climatological spinup, the ocean model was run interannually spanning the period 1979-present. This 1/32° interannual simulation shows increased realism and accuracy compared to its 1/16° counterpart (run under an earlier DoD Challenge project) attributable to the increase in horizontal resolution. An example illustrating the value added of finer resolution is shown in Figure 1.

Figure 1 shows a comparison of sea surface height (SSH) variability in the Gulf Stream region from the 1/16° and 1/32° global models and from Topex/Poseidon altimeter data for 1979–1999. The pattern and amplitude of the variability reveals valuable information about the models' ability to simulate specific features of the flow field. In the 1/32° model the high variability extends farther to the east and matches the pattern and amplitude from Topex/Poseidon much better. However, the northeastward extension of variability east of 47°W is too weak in both models, although it is still a region of high model variability in comparison to most ocean regions. Starting from west to east, all three show the narrow band of very high variability west of 68°W and a broadening east of that longitude. There is a local bulge of high variability to the south in the region of the New England Seamount Chain, but the 1/32° model shows better longitudinal agreement with Topex/Poseidon. Between 45°W and 50°W the 1/32° model and Topex/Poseidon show a corridor of high variability wrapping around the nonlinear recirculation gyre, which is lacking in the 1/16°

model. This shows that the 1/32° model simulates realistic eastward penetration for the nonlinear recirculation gyre.

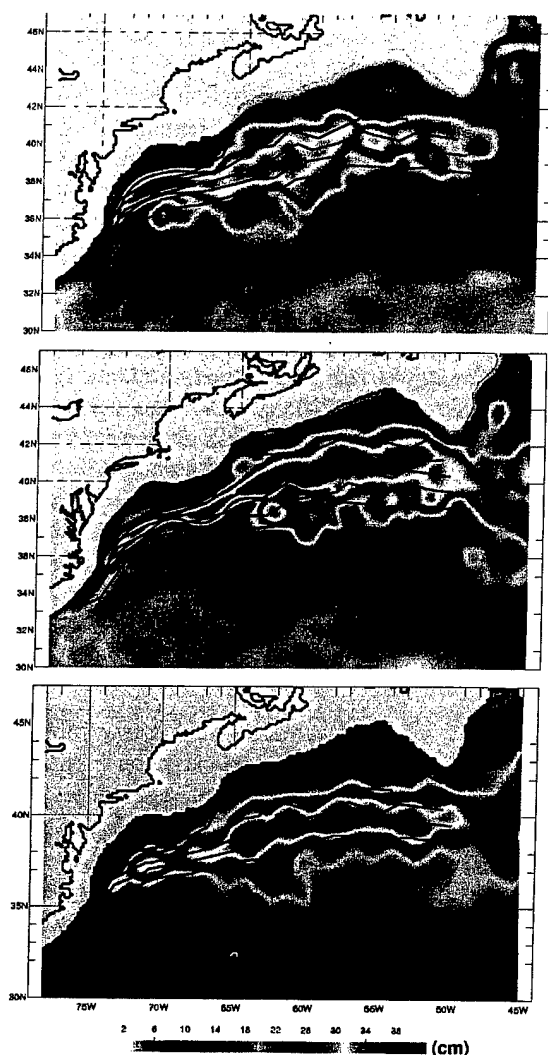**Figure 1. Comparison of SSH variability (1979–1999) between the 1/16° (upper panel) and 1/32° global models (middle panel) and analysis of Topex/Poseidon data (lower panel) by Jacobs (NRL). The 5 lines overlaid on each SSH variability plot are the Gulf Stream mean axis (center), standard deviation about the mean axis and extreme positions determined from Topex/Poseidon data (Lee et al., 1997).**

Statistics from comparisons (1997–1999) of modeled vs. observed SSH for 104 tide gauge locations throughout the world ocean are shown in Figure 2. The modeled SSH is able to generally reproduce the observed sea level fluctuations well, with a median correlation of .62. The regions of highest correlation coincide with regions in the tropics and along eastern boundaries. There are several

regions, however, where the correlations are either low or negative. Typically, these are regions where the SSH variability is a nondeterministic response to atmospheric forcing due to flow instabilities. In these regions ocean data assimilation helps greatly in reproducing specific features of the observed variability such as individual current meanders and eddies (e.g., Hurlburt et. al., 2002).
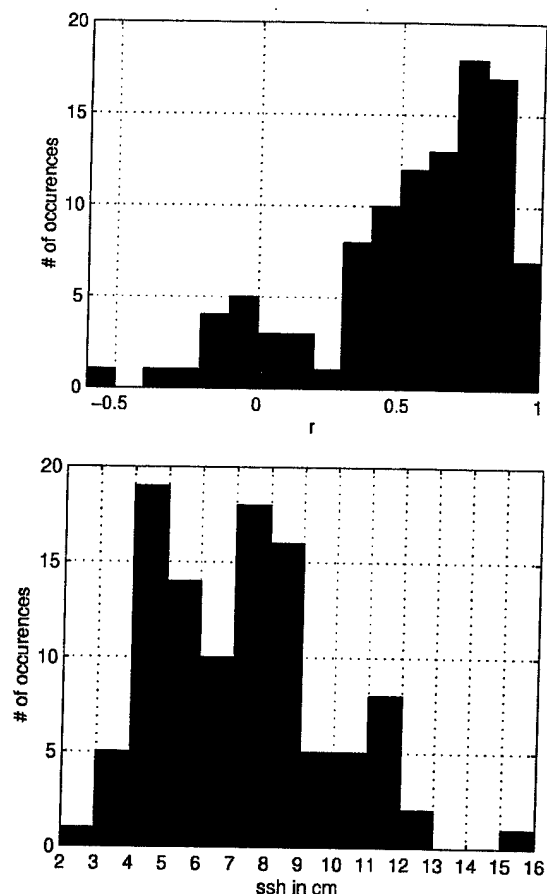

Figure 2. NLOM vs observed monthly sea level correlation (upper panel) and RMS difference (lower panel) statistics at 104 locations throughout the world ocean from the years 1979–1999. The median correlation is .62 and the median RMS difference is 7.2 cm.

Ocean nowcast experiments with data assimilation initialized from the interannually forced simulation are currently ongoing. The 1979–present interannual model results were used to generate statistics and a model SSH mean for use in these data assimilative experiments. The model is assimilating SSH from 3 satellite altimeters (ERS-2, GFO and JASON-1) and sea surface temperature from satellite IR imagery. Assimilation of satellite altimeter data is critical in allowing the model to map individual current meanders and eddies (see Figure 3).
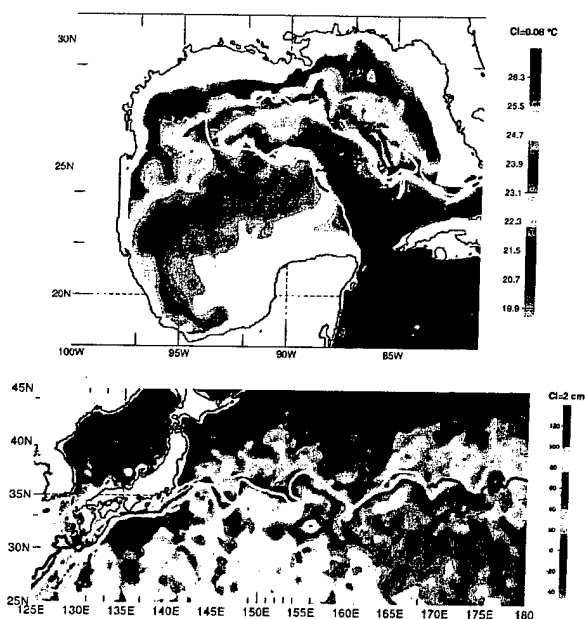
Figure 3. Sea surface temperature for 11 Feb 2002 (upper panel) and sea surface height for 2 May 2002 (lower panel) from the data assimilative model. Note the good agreement between modeled features and operational satellite IR frontal analyses performed by NAVO (overlaid black and white lines). The black line segments are based on IR data > 4 days old.

We are currently testing, evaluating and tuning the data assimilation technique used. The remainder of this fiscal year we will complete the ocean nowcast experiments with data assimilation and perform ocean forecast experiments. The completed system is planned for transition to NAVO later in 2003.

4. Significance to DoD

Applications for this nowcast/forecast system include assimilation and synthesis of global satellite surface data; ocean prediction; optimum track ship routing; search and rescue; anti-submarine warfare and surveillance; tactical planning; high resolution inputs for other models and shipboard environmental products; environmental simulation and synthetic environments; observing system simulations; ocean research; pollution and tracer tracking and inputs to water quality assessment.

5. Systems Used

IBM SMP at NAVO MSRC

6. CTA

Climate/Weather/Ocean (CWO)

Acknowledgments

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